THE ASTROPHYSICAL JOURNAL, 467:162–167, 1996 August 10

CAN ELECTROMAGNETIC INSTABILITIES DRIVEN BY TEMPERATURE GRADIENTS INHIBIT THERMAL CONDUCTION IN CLUSTER COOLING FLOWS?

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Received 1995 May 1; accepted 1996 February 8

ABSTRACT

It is proposed that electromagnetic instabilities driven by temperature gradients can inhibit thermal conduction in intracluster gas. The suppression of the heat flux is due to rapid pitch-angle scattering by the self-excited waves. For typical parameters, the heat flux is inhibited by up to 3 orders of magnitude below the classical value in the outer parts of the inflow. This reduction may allow for the formation of a moderate homogeneous cooling flow, though not enough to allow the homogeneous flow to become supersonic.

The transition to a multiphase cooling flow is also considered, and it is shown that this inhibition mechanism may reduce the thermal conductivity by the factor required for thermal instability to develop in the outer parts ($R > 30$ kpc) and for radiative cooling to quench evaporation of the cooled condensations in the central region of the flow.

Subject headings: cooling flows — instabilities — intergalactic medium — MHD

1. INTRODUCTION

The role of heat conduction in clusters of galaxies is yet unclear (Bertschinger & Meiksin 1986; David, Hughes, & Tucker 1992). However, the existence of large amounts of relatively cold gas in juxtaposition with a hot phase in the center of many clusters of galaxies is evident from X-ray observations. The widely accepted model for explaining the observations is the cooling flow model (for a recent review see Fabian 1994).

It has long been argued that the presence of cooler gas in the center of the very hot intracluster medium implies that heat conduction must be reduced well below the classical value (Binney & Cowie 1981). Suppression of heat conduction is frequently and routinely attributed to tangled magnetic fields (Fabian 1994). But we know of no serious theory of how the field is uniformly and consistently maintained in a sufficiently tangled state to suppress radial heat conduction by 2 orders of magnitude. Since it is widely suspected that the field energy exceeds the kinetic energy of the inflow, the assumption of a highly tangled field in an otherwise spherically symmetric model seems especially strong. The prominent difficulty associated with this mechanism is that sufficient inhibition requires dynamically important fields in models that have appeared to date (Binney & Cowie 1981; Rosner & Tucker 1989). Pistinner & Shaviv (1996, hereafter PS96) and Tao (1995) have recently criticized the tangled-field hypothesis in greater detail. Tribble's (1989) phenomenological approach, which suggests that heat flux suppression by tangled magnetic field is possible, does not account for the dynamical importance of the field.

A transition to a *multiphased* cooling flow induced by linear hydrodynamical perturbations requires the presence of magnetic fields (Balbus & Soker 1989; Loewenstein 1990; Balbus 1991), although even relatively weak fields are sufficient. An alternative is anomalous viscosity (Pistinner 1996, hereafter P96). However, even then the heat flux must be inhibited by at least 4 orders of magnitude, by some mechanism other than tangled magnetic field (Balbus 1991). But again, Tribble's (1989) mechanism may obviate the need for linear instability.

Several authors have argued that a cooling flow model may not be needed if there exists some external heat source that can counterbalance radiative cooling and maintain the warm phase at a moderate temperature (but still cooler than the hot phase, as implied by present observations). This scenario has been criticized on both observational and theoretical grounds (e.g., Fabian 1994). However, irrespective of its validity, this model also requires strong heat flux inhibition.

This paper examines the role of electromagnetic instabilities driven by temperature gradients in the evolution of cooling flows. Some of the X-ray emission appears to come from gas that is significantly cooler than the hot phase. A self-consistent model without fine tuning should explain why this curious situation arises nearly consistently in clusters, and the details of heat conduction seem a necessary ingredient to the eventual conclusion of such a model. Thus, the commonly accepted view is that in order to account for the observations, Spitzer heat conduction (Spitzer 1962) is reduced in the inner 100–200 kpc of cooling flow clusters of galaxies.

In the presence of temperature gradients the electron distribution function becomes locally anisotropic. As long as the characteristic mean free path of the heat flux carrying electrons, $\lambda_e(v)$, is much smaller than the temperature gradient length scale, denoted here by L_T, the anisotropy is essentially small, typically on the order of λ_e/L_T. One can then employ the standard perturbation theory (Chapman-Enskog expansion), whereby the distribution function is expanded around a Maxwellian in powers of the parameter $\epsilon(v) = \lambda_e(v)/L_T$ (also known as the Knudsen parameter), viz., $f = f_m + \epsilon f_1 + \epsilon^2 f_2 + \cdots$. Then one solves the corresponding Fokker-Planck equation, restricted to the zero-current requirement, for the next order correction, f_1, and subsequently calculates the heat flux $\boldsymbol{q} = \langle mv^2 \boldsymbol{v} f \rangle = \langle mv^2 \boldsymbol{v} f_1 \rangle + O(\epsilon^2)$, where the angular brackets denote an integral over momenta. This approach has been used extensively in the literature to compute the transport coefficients in many situations. It can be readily shown that the heat flux thereby obtained is proportional to the Knudsen parameter of thermal electrons, namely, $\epsilon_T \equiv \epsilon(V_e)$, where

$$V_e = \sqrt{\frac{k_B T}{m_e}} \approx 3.9 \times 10^9 \left(\frac{T}{10^8 \text{ K}}\right)^{1/2} \text{ cm s}^{-1} \qquad (1)$$

is the electron thermal speed. Now, the heat flux is carried predominantly by electrons having velocities in the range 2–4 times V_e; consequently, in the case of Coulomb collisions, for which the mean free path increases with electron velocity as v^4, perturbation theory breaks down when ϵ_T approaches $\sim 10^{-2}$ and not unity as often mistakenly assumed. This problem has long been recognized (e.g., Cowie & McKee 1977; Shvarts 1985; Luciani & Mora 1985). Numerical simulations indicate that the heat conduction is smaller by more than an order of magnitude than the classical value when $\epsilon_T \gg 10^{-2}$ (for a review see Max 1981). The estimate of the heat transport coefficient in the regime of saturated conduction is complicated considerably by nonlocal effects (e.g., Balbus & McKee 1982; Chun & Rosner 1993; Bandiera & Chen 1994a, 1994b). The problem of saturated heat conduction has been considered recently in astrophysical contexts by Bandiera & Chen (1994a, 1994b), who emphasized the role played by the electrostatic barrier produced by the superthermal electrons permeating the cold medium in reducing the conduction transport.

Heat flux inhibition by plasma instabilities has been studied in the context of fusion pellet plasma (e.g., Ramani & Laval 1978; Okada, Yabe, & Niu 1977; Max 1981; Galeev & Natanzon 1991), the solar wind (e.g., Forslund 1970; Gary et al. 1975), and recently in the context of cluster cooling flows (Jafelice 1992) and evaporation of clouds in the interstellar medium (Levinson & Eichler 1992, hereafter LE92). In § 2 we summarize the model of heat flux inhibition by electromagnetic instabilities proposed by LE92, and the basic results, which we then apply in § 3 to cooling flows. We summarize in § 4.

2. THE HEAT FLUX INHIBITION MODEL

The effect of fully developed turbulence on the transport properties of a plasma, so-called anomalous transport, is a problem of considerable interest in plasma physics and astrophysics (e.g., Tsytovich 1972). The idea underlying the anomalous transport mechanism is rather simple: plasma instabilities driven by temperature gradients (or electric currents in other situations) may give rise to fully developed turbulence that will, in turn, tend to isotropize the electron distribution via collective wave-particle interactions, thereby reducing the heat flux substantially, provided that the effective pitch-angle scattering rate by the waves largely exceeds the Coulomb collision rate. The suppression of the heat transport depends on the nature of the instability and the saturation mechanism.

The heat flux inhibition mechanism proposed by LE92 involves the excitation of short-wavelength electromagnetic modes *by the heat flux carrying electrons.* For a wide range of parameters, relevant to most astrophysical systems including cooling flows, the unstable modes are found to be whistlers. The saturation level of the instability and, hence, the level of heat conduction depend on the rate of energy removal by collisional damping, escape, or nonlinear processes.

The (over) simplified assumption made by LE92 is that the effective scattering rate of relevant electrons is independent of electron momentum, thereby excluding the possibility of quasi-linear saturation. Under this assumption, the electron pitch-angle scattering rate due to collective wave-particle interactions, ν_{eff}, is constant. The Knudsen parameter can be defined in terms of the effective scattering rate as $\epsilon_{\text{eff}} = V_e/(\nu_{ei} + \nu_{\text{eff}})L_T$. Thus, when the instability is unimportant; that is, when $\nu_{\text{eff}} \ll \nu_{ei}$, $\epsilon_{\text{eff}} \simeq \epsilon_T$. When the scattering rate due to waves starts exceeding the Coulomb collision rate, ϵ_{eff} becomes much smaller than the classical value ϵ_T. The saturation level of the instability is determined by energy loss processes (as opposed to quasi-linear saturation), among which, it is found, mode coupling dominates (a rigorous derivation of the induced scattering rate due to mode coupling and nonlinear Landau damping is given in Levinson 1992).

With the above prescription, the maximally unstable wavelength (measured henceforth in units of the gyroradius of thermal electrons, i.e., $x_M = \Omega_e/k_M V_e$, where Ω_e is the electron gyrofrequency) and ϵ_{eff} are governed by the coupled equations (LE92)

$$x_M^5 \frac{\epsilon_{\text{eff}}}{2}\left(2 + \frac{\beta}{2}\right) - x_M^2\left(1 - \frac{\beta}{2}\epsilon_{\text{eff}}^2\right) - 3 = 0 \qquad (2)$$

and

$$\sqrt{2\beta_e}\,\frac{L_T \omega_{\text{pe}}}{c}\left(\frac{\epsilon_{\text{eff}}}{2}\right)^2 g(x_M) \times \exp\left(-\frac{1}{2}x_M^2\right)(1 + x_M)^2 - 1 = 0\,, \qquad (3)$$

where again L_T is the temperature gradient length scale, β is the ratio of electron thermal pressure to magnetic pressure, ω_{pe} is the corresponding electron plasma frequency, and

$$g(x_M) \simeq \begin{cases} 1\,, & x_M < 1\,, \\ x_M^2\,, & x_M > 1\,. \end{cases} \qquad (4)$$

It should be emphasized that the value of ϵ_{eff} thereby obtained is highly insensitive to the nonlinear damping rate and other parameters because the growth rate declines very steeply with decreasing ϵ_{eff}. On the other hand, it might depend on the assumptions of the model (LE92).

3. APPLICATION TO CLUSTER COOLING FLOWS

In this section we incorporate the heat flux suppression mechanism discussed in the preceding section into the cooling flow model.

It has long been argued that the homogeneous cooling flow model appears to be in conflict with X-ray observations (e.g., Fabian, Nulsen, & Canizares 1991; Fabian 1994), and that a multiphase model is required. The presence of cold gas inferred from spectroscopy of the central region of a cluster of galaxies (e.g., Canizares, Markert, & Donahue 1988) provides additional support for the multiphase cooling flow model. Nevertheless, we find it instructive to explore the effect of heat flux inhibition on the homogeneous flow, because it serves as the unperturbed solution employed in the linear analysis of thermal instability by many authors. In § 3.1 we calculate $\epsilon_{\rm eff}$ for underlying homogeneous and multiphase cooling flows, and compare the results. We then go on to examine in § 3.2 the effect of conduction suppression by electromagnetic instabilities on the growth of small (linear) density fluctuations, using the same linear stability analysis technique employed by Balbus (1991). We find that this mechanism can account for the reduction in heat conduction required to allow for the thermal instability to develop and form condensations.

3.1. *Heat Flux Suppression in Cooling Flows*

The structure of the spherically symmetric, weakly magnetized, homogeneous cooling flow is dictated by the continuity, momentum, and energy equations:

$$\dot{M} = 4\pi r^2 v(r)\rho(r) ,$$

$$\rho(r)v(r)\frac{dv(r)}{dr} = -\frac{dP(r)}{dr} + \rho(r)\frac{d\Phi(r)}{dr} + O(\beta^{-1}) ,$$

$$\frac{3}{2}P(r)v(r)\frac{d}{dr}\ln[P(r)\rho(r)^{-5/3}] + \rho(r)^2\Lambda(T) = B\frac{\partial}{\partial l_{\parallel}}\left[\left(\frac{1}{B}\frac{\epsilon_{\rm eff}}{\epsilon_T}\right)\kappa_S\frac{\partial T}{\partial l_{\parallel}}\right], \quad (5)$$

where κ_S is the Spitzer thermal conductivity, Φ is the gravitational potential,

$$\frac{\partial}{\partial l_{\parallel}} = \left(\frac{\boldsymbol{B}}{B}\right)\cdot\nabla , \quad B = |\boldsymbol{B}| , \quad (6)$$

and $\boldsymbol{B}$ is the magnetic field vector. In this picture, the ratio $\epsilon_{\rm eff}/\epsilon_T$ represents the suppression of heat conduction relative to the Spitzer (classical) value due to the electromagnetic instability discussed in § 2. We note that any plasma turbulence which affects only one component of the plasma (e.g., electrons) cannot affect the radiation process, since they involve collisions between electrons and ions. Consequently, the cooling function should not be affected by the presence of turbulence.

This set of equations must be supplemented by equations determining the magnetic field profile and $\epsilon_{\rm eff}(r)$, as will be described below. Equations (5) together with the equations for the magnetic field and $\epsilon_{\rm eff}$ can be integrated now to yield the structure of the inflow. This is rather complicated and will not be done here. Instead, we shall assume a priori that heat conduction is negligible, i.e., we set $\epsilon_{\rm eff}/\epsilon_T \to 0$ in equations (5), and then use the solution of equations (5) in the absence of heat conduction to obtain the cooling flow parameters at any given radius, which are subsequently used to determine $\epsilon_{\rm eff}(r)$. The neglect of heat conduction is justified a posteriori using the suppression factor thereby obtained.

Numerical solutions of equations (5) for the temperature, density, and velocity profiles (the velocity is required to calculate the magnetic field structure in the cooling flow domain) are given in the literature (White & Sarazin 1987). The structure of the magnetic field is taken to be that calculated analytically by Soker & Sarazin (1990) and generalized by Pistinner & Shaviv (1995, hereafter PS95). In doing so we follow the assumption made by Soker & Sarazin (1990), namely, that the field lines would straighten prior to driving a significant turbulent flow. The magnetic field profile is then given by

$$B_r = B_r^{\infty}(r_\infty, \theta, \phi)\left(\frac{r}{r_\infty}\right)^{-2} , \qquad B_T = B_T^{\infty}(r_\infty, \theta, \phi)\left(\frac{r}{r_\infty}\right)^{-1}\left(\frac{v}{v_\infty}\right)^{-1} , \quad (7)$$

where quantities labeled by ∞ are given on the edge of the cooling radius, B_r is the radial component of the field, and B_T denotes each of the transverse components of the field, θ and ϕ. Note that in general $B_\theta \neq B_\phi$. Using this solution, we then compute $\beta(r)$ and $\omega_{\rm pe}(r)$

Recent work (PS95) has demonstrated that in order to sustain spherically symmetric flow the field must be purely radial, viz., $B_T = 0$. However, in view of the fact that the sound speed is expected to exceed the Alfvén speed considerably in most of the cooling flow domain, it is likely that nonradial, long-wavelength magnetic field fluctuations will be absorbed by small pressure and density fluctuations, at least as long as $\beta > 10$, and thus will prevent the development of a significant nonradial flow. This could be seen from the approximation $\partial \ln(P)/\partial(\theta, \phi) \approx 1/[4\pi\beta_e(r)](r/l_B)$, where $l_B = 10$ kpc is the coherence length of the field. We therefore neglect the back-reaction of the magnetic field on the flow throughout most of the cooling flow region. We expect this assumption to hold for $\beta_e(r) > 10$. The magnetic field profile invoked by Soker & Sarazin (1990) (which uses a 1 μG magnetic field at the cooling radius) appears to be supported by recent Faraday rotation measurements in cooling flows (Owen, Eilek, & Keel 1990; Ge 1991; Perley & Taylor 1991; Ge & Owen 1993; but cf. Bicknell, Cameron, & Gingold 1990; Zoabi, Soker, & Regev 1996).

We choose as our standard model the homogeneous model of White & Sarazin (1987) with an accretion mass rate $\dot{M} = 300\ M_\odot\ {\rm yr}^{-1}$. The numerical value of the magnetic field at the cooling radius is estimated from the lack of a hard X-ray power-law tail and is taken to be 1 μG (Sarazin 1986). This field strength agrees well with the predictions of Soker & Sarazin (1990) and with the observations of Owen et al. (1990), Ge (1991), Perley & Taylor (1991), and Ge & Owen (1993). Next, we use this model with the magnetic field structure adopted above as input to compute $\epsilon_{\rm eff}$ as a function of radius. This is done by solving equations (2) and (3) simultaneously, using the Newton-Raphson method, at any given radius.

The results are exhibited in Figure 1. The effective Knudsen number at the edge of the flow is about 10^{-5}. It is clearly seen that the suppression factor at the cooling radius is about 10^{-3}, corresponding to a reduction of the mean free path by a factor 10^{-3} relative to the electron-ion collision length. Such a suppression of the heat flux justifies the neglect of heat conduction in the homogeneous model (Binney & Cowie 1981; Fabian 1994).

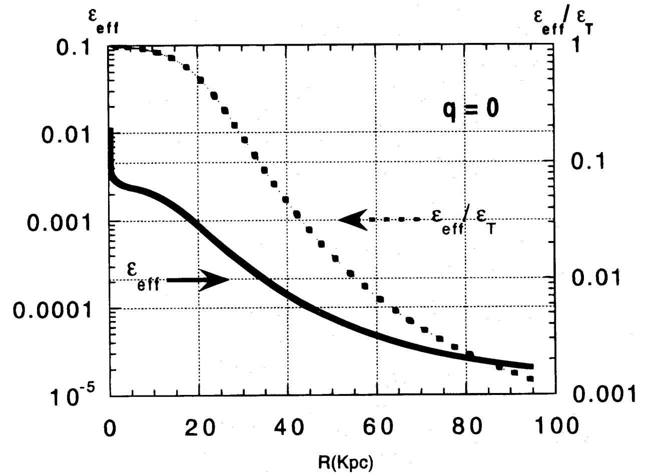

FIG. 1.—Effective Knudsen number and corresponding suppression factor computed with an underlying homogeneous cooling flow model ($q = 0$).

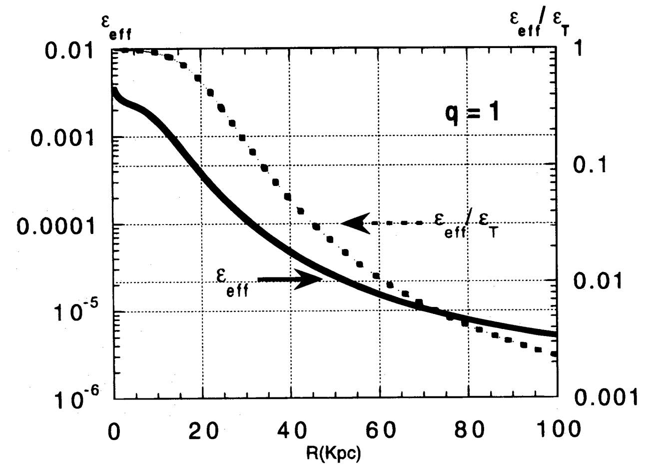

FIG. 2.—Same as Fig. 1, but for an underlying multiphase model (White & Sarazin 1987 with $q = 1$).

The foregoing analysis suggests that the steady state model of White & Sarazin (1987) is consistent, at least in the outer parts of the cooling flow. We anticipate that a self-consistent treatment, that is, taking into account the effect of the inhibited heat flux in the last of equations (5), will alter the solution somewhat in the innermost parts of the cooling flow, where the suppression factor is smallest. In particular, as explained by LE92, the inhibition model proposed here is rendered suspect once $\epsilon_{\rm eff}$ becomes smaller than about $0.02\beta_e^{-1}$, at which point quasi-linear saturation will prevent further suppression of the heat flux. *We therefore suspect that the homogeneous flow would not become supersonic and that the gas in the inner parts would not be able to cool well below* 10^7 K. The structure of the outer parts is expected to remain unchanged. The resulting homogeneous flow is likely to correspond to an accretion breeze solution rather then a supersonic one.

In the case of multiphase flow, equations (5) must be modified to take account of the mass loss due to cooling condensations dropping out of the background flow. To illustrate how this might affect the heat flux suppression, we adopt the White & Sarazin (1987) model with efficient star formation rate ($q = 1$ in their notation), and recalculate $\epsilon_{\rm eff}$ and the suppression factor in the background flow. The results are depicted in Figure 2 and compared with those obtained for the homogeneous model ($q = 0$) in Figure 3, from which it is seen that the formation of a cold phase (with small volume filling factor) has little effect on the level of heat flux inhibition.

3.2. *The Development of Thermal Instability in the Presence of Inhibited Heat Flux*

The transition to a multiphase cooling flow has been discussed by many authors, most of which emphasized the requirement for strong suppression of heat conduction. Mathews & Bregman (1978) have argued that in the absence of heat conduction, radial perturbations grow on a cooling timescale. This conclusion was verified later by White & Sarazin (1987). Malagoli, Rosner, & Bodo (1987) and Balbus & Soker (1989) have shown that in the unmagnetized case the growth of density perturbations is very slow and would not lead to highly overdense regions, because the background flow is convectively stable. Nulsen (1986) has pointed out that the presence of magnetic fields is likely to enhance the thermal instability. Loewenstein (1990) and Balbus (1991) have provided a detailed analysis of magnetized cooling flows, and have shown that weak magnetic fields suffice to destabilize the flow and to allow for the cooling of the overdense gas. However, as argued by Balbus (1991), for typically inferred values of the magnetic fields in those systems the thermal conductivity must be reduced by several orders of magnitude below the Spitzer (classical) value in order for thermal instability to be present. Furthermore, in the framework of Balbus (1991), the field is assumed to be ordered on the scale of the perturbations, and this assumption does not admit a tangled field (P96). Thus, such a reduction must be accomplished by means other than tangled magnetic field; Balbus (1991) qualitatively suggested plasma collective effects.

We note here that the naive use of the Spitzer conductivity in such situations is likely to result in an overestimate of the heat flux by a large factor. The reason is that the mean free path for interparticle collisions exceeds, quite generally, the characteristic size of the overdense (unstable) regions, thereby giving rise to saturation and nonlocal effects. This is demonstrated by P96, who incorporated nonlocal heat conduction effects in the stability analysis of Balbus (1991), using a simple model of nonlocal transport. They have

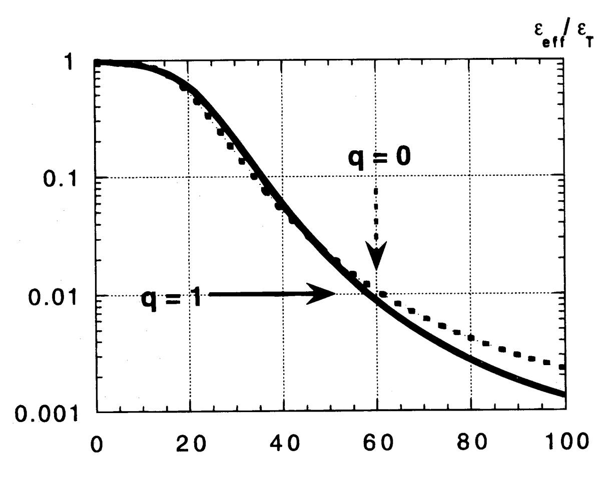

FIG. 3.—Comparison between the suppression factors obtained for homogeneous and multiphase models.

found that perturbations which have a scale much smaller than the interparticle collision mean free path can condense by virtue of the fact that only a small fraction of the energy carried by the heat-conducting electrons is deposited in the overdense regions. However, this reduction cannot account for the formation of a homogeneous flow, which serves as the unperturbed model. On the other hand, the presence of collective plasma instabilities may render the effective mean free path far smaller than the size of condensation modes, in which case the analysis of P96 might be irrelevant. In such a case the suppression is essentially due to the enhanced (effective) scattering rate. In this section we apply the inhibition mechanism proposed in § 2 to the formation of a multiphase cooling flow and examine whether it can provide the required suppression of heat conductivity.

Following Balbus (1991), we consider the growth of noncompressive density perturbations (i.e., $\delta P = 0$, where P is the pressure of the background flow) in a steady, radial, weakly magnetized flow. Whistler turbulence, driven by the temperature gradients in a manner described in § 3, will be present in this background flow. We denote by $\lambda_{\rm hyd}$ the wavelength of some given unstable condensation mode, and suppose that it is a fraction ζ of the temperature gradient length scale of the unperturbed medium, i.e., $\lambda_{\rm hyd} = \zeta L_T$. We next repeat Balbus's analysis using the effective heat flux, $q_{\rm eff} = (3/4)\epsilon_{\rm eff}\, m_e/m_p\, \rho V_e^3$, where m_p is the proton mass. To a good approximation the perturbed effective heat flux is

$$\delta q_{\rm eff} \simeq -\epsilon_{\rm eff}\, \frac{m_e}{m_p}\, \rho V_e^3 \left(\frac{\delta\rho}{\rho}\right) \simeq -q_{\rm eff}\left(\frac{\delta\rho}{\rho}\right), \qquad (8)$$

independent of $\lambda_{\rm hyd}$. The term $\delta\epsilon_{\rm eff}$ is negligibly small because $\epsilon_{\rm eff}$ is highly insensitive to the flow parameters, as explained in LE92. To first order in $\lambda_{\rm hyd}/r \simeq \zeta$, the perturbed Spitzer heat flux can be written as

$$|\,\delta \boldsymbol{q}_{\rm S}\,| \simeq \kappa_{\rm S}\,|\,\nabla\,\delta T\,| \simeq -\kappa_{\rm S}\left(\frac{T}{\lambda_{\rm hyd}}\right)\left(\frac{\delta\rho}{\rho}\right) \simeq -q_{\rm S}\,\zeta^{-1}\left(\frac{\delta\rho}{\rho}\right). \qquad (9)$$

Thus, the suppression factor for the perturbed heat fluxes is

$$\frac{\delta q_{\rm eff}}{\delta q_{\rm S}} \simeq \zeta\, \frac{\epsilon_{\rm eff}}{\epsilon_T}\,. \qquad (10)$$

In deriving the above results, we have used the fact that the growth time of the plasma instability is much shorter than any hydrodynamical timescale, so that the level of whistler turbulence in the vicinity of a growing condensation is adjusted essentially instantly to temporal changes of the flow parameters. The suppression factor computed in equation (10) is proportional to the global suppression factor times the ratio of the condensing mode length to the background flow scale height, and it is clearly seen that the reduction required to ensure thermal instability, namely, $\delta q_{\rm eff}/\delta q_{\rm S} < 10^{-4}$, can be readily obtained, within the framework of our model, in most parts of the cooling flow, with the exception of the inner 30 kpc or so. However, we expect that by the time the condensations reach the inner part of the cooling flow, their density and, hence, their cooling rate have increased substantially, in which case only mild if any conduction suppression is required to prevent rapid evaporation of the cold phase, particularly the large condensations.

As shown by Cowie & McKee (1977) in the context of interstellar clouds, when ϵ becomes smaller than about 10^{-2}, radiative cooling halts evaporation of the clouds into the hot phase. From Figure 1 it is seen that the value of $\epsilon_{\rm eff}$ even at very small radii is of order 10^{-3}. Therefore, we expect the cold, line-emitting material that dropped from the outer cooling flow region to survive there. The presence of cooled filaments in the inner parts of cluster cooling flows, inferred from spectroscopic observations, appears to be consistent with this view. Alternatively, the observed filaments might be associated with magnetic collimation, which requires the inflow to be mildly subsonic with rough equipartition between the gas and magnetic field energy (PS95), in agreement with the results of § 3.1. We comment here that in spite of some evidence for excess X-ray absorption in cooling flows, the lack of direct detection of the cooled component in the central region is as yet an open issue.

4. SUMMARY

We have shown for a specific model of electromagnetic turbulence driven by temperature gradients that heat conduction is inhibited by about the amount required for the formation of a homogeneous (and a self-consistent multiphase) flow. However, it seems that the suppression in the inner ~30 kpc is insufficient to allow a supersonic flow to develop.

Transition to a multiphase cooling flow (from the homogeneous phase), as suggested by Loewenstein (1990) and Balbus (1991), seems more likely and also required by the observations. The large conduction suppression obtained in the outer parts of the flow may account for the growth of linear density perturbations, which will subsequently condense and drop into the central region. Although the suppression factor in the inner 30 kpc is much smaller than in the outer parts, the value of ϵ computed in the inner parts appears to be small enough to allow radiative cooling to quench the evaporation of the condensed clouds. However, in view of the limitation of our analysis, which basically simplifies pitch-angle scattering to a BGK operator, further work may be required to establish whether this mechanism can indeed account for the suppression of thermal conductivity required by the multiphase cooling flow model. In particular, the role of off-axis waves and firehose-unstable distributions needs to be examined. The preliminary results presented in this paper are encouraging, and motivate further analysis in this direction.

A. Levinson acknowledges helpful discussions with A. C. Fabian and support from NASA through grant NAG 5-3097, and NSF through grants AST 91-19475 and 93-15375, S. P. and D. E. were supported in part by the Israeli BRF and the Israeli academic planning and budgeting committee.

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